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Effects of similarity on apparent motion and perceptual grouping

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Abstract. Effects of similarity in colour, luminance, size, and shape on apparent motion and perceptual grouping were examined in part 1 in two parallel experiments on the same seven subjects. In both experiments, the effect of similarity was compared with that of proximity in competitive, bistable stimulus situations. A combination of a larger horizontal separation between the homogeneous stimulus elements and a smaller constant vertical separation between heterogeneous stimulus elements produced two kinds of apparent motion (or perceptual grouping) with equal probabilities. Such matched separations between homogeneous stimulus elements were obtained by the double staircase method in various stimulus conditions. In both experiments on apparent motion and perceptual grouping matched separation was found to increase as the difference between the heterogeneous stimulus elements increased. High correlations (0.71 to 0.94) of matched separations were found between apparent motion and perceptual grouping in four stimulus series: colour, luminance, size, and shape. Six of the seven subjects were also tested in part 2. Here, the effects of differences were found to work additively across different perceptual attributes in both phenomena, when multiple differences were combined in heterogeneous elements. The experimental results are discussed from the point of view that apparent motion is an example of perceptual constancy.

1 Introduction

Wertheimer (1923) pointed out that similarity, as well as proximity, among others are important factors in perceptual grouping. Proximity has also been found to be one of the determining factors of apparent motion (beta motion) as shown by Korte's law (Koffka 1935). It was much later that the effect of similarity on apparent motion was studied systematically (Kolers 1972).

More recently, this problem was investigated from the point of view of correspondence (Ullman 1979, 1980). Correspondence strength was found to increase with increasing similarity in perceptual attributes (colour, brightness, shape, size, etc) between the two stimulus elements and decrease with increasing distance between them (Cavanagh et al 1989; Dobkins and Albright 1993; Green 1986, 1989; He and Nakayama 1994; Mack et al 1989; Nishida and Takeuchi 1990; Shechter et al 1988; Shechter and Hochstein 1989).[(1)]

From a different point of view, Oyama (1997) postulated that apparent motion could be interpreted as an outcome of perceptual organisation that strives to maintain constancy and to avoid changes as far as possible. Apparent motion can serve to keep other perceptual attributes constant, where motion is the smallest possible change resulting from perceptual organisation under a given stimulus condition. Both similarity

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(1) Nishida and Takeuchi (1990) found that the affinity of apparent motion monotonically increased with increasing the luminance of either element of the matching pair in the split/fusion motion display in their experiment 1, but the luminance similarity served as a correspondence cue in the ambiguous motion display in their experiment 3.

and proximity between successively presented stimulus elements reduce perceptual changes and, consequently, they should be important factors for apparent motion. The present paper provides an experimental basis supporting Oyama's (1997) theoretical arguments.

In the present study, the effects of similarity in colour, luminance, size, and shape on apparent motion and perceptual grouping were examined in two parallel series of experiments on the same subjects. In both series, the effect of similarity was juxtaposed with that of proximity in competitive, bistable stimulus situations, as in studies on apparent motion by He and Nakayama (1994), Ramachandran and Anstis (1985), von Schiller (1933; see Koffka 1935), and Shechter et al (1988), etc; and in studies on perceptual grouping by Hochberg and Silverstein (1956), Oyama (1961), and Wertheimer (1923) (see figures 1 and 2). If the similarity factor was stronger than the proximity factor in a given stimulus condition, both apparent motion and perceptual grouping were expected to occur (horizontally in figures 1 and 2) between stimulus elements of the same colour, luminance, size, or shape. But if the proximity factor was stronger, these phenomena were expected to occur (vertically) between closer stimulus elements with different perceptual attributes. A suitable combination of a certain greater horizontal separation between the homogeneous stimulus elements and a smaller constant vertical separation between heterogeneous stimulus elements will produce vertical and horizontal apparent motion (or perceptual grouping) with equal probabilities. The effects of the two factors are matched in this combination, as pointed out by Shechter and Hochstein (1989). Such matched separations were measured separately for apparent motion and for perceptual grouping in the following experiments.

2 Method and conditions

2.1 *Subjects*

Six graduate students and one researcher (the third author) in psychology served as subjects. One of the graduate students participated only in part 1, while the others participated in both parts 1 and 2. All had normal or corrected-to-normal visual acuity and normal colour vision.

2.2 *Stimuli*

In both apparent-motion and perceptual-grouping experiments, stimulus patterns such as figures 1 and 2, respectively, were presented on the monitor of a personal computer (NEC PC 9801) at 57 cm from the subject's eyes.

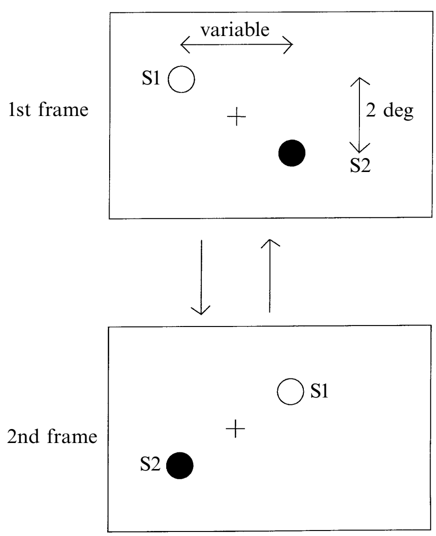

Figure 1. Schematic representation of stimulus patterns used in the apparent-motion experiment (Oyama 1997).

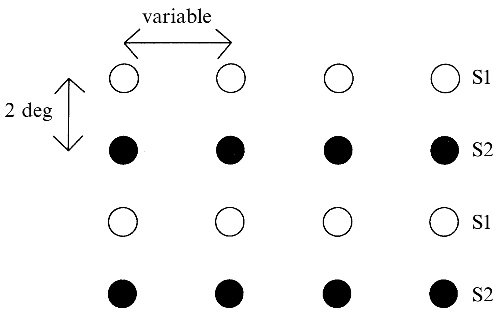

Figure 2. Schematic representation of stimulus patterns used in the perceptual-grouping experiment (Oyama 1997).

In apparent-motion experiments, two frames shown in figure 1 were presented alternately with a duration of 150 ms and an ISI of 150 ms in part 1; and with a duration of 80, 100, or 150 ms and an ISI of the same length as the duration in part 2, for ten cycles of stimulus alternations. The subject was asked to tilt a joystick to the right when the stimulus elements were seen to move horizontally, and to pull it when they were seen to move vertically. The horizontal separation between the homogeneous stimulus elements was increased after a subject's "horizontal" response and decreased after a "vertical" response in a step of 15 min of visual angle, while the vertical centre-to-centre separation between the heterogeneous stimulus elements was kept constant (2 deg).

In a preliminary experiment, a strong persistence of apparent motion direction was found. For example, if horizontal motion occurred once, it persisted even when horizontal separation was increased in many steps. The same tendency was observed for vertical motion. This kind of perceptual persistence or hysteresis had been found earlier by Metzger (1953), Shechter and Hochstein (1989), Wertheimer (1912; see Kolers 1972; Sekuler 1996) and systematically studied by Hock et al (1993, 1996) and Sumi (1980). Shechter and Hochstein (1989) inserted correction trials with a very different proximity to prevent the subjects from locking into perceiving motion in a single direction. In the present experiment, a distractor stimulus was inserted after every ten cycles of alternations of the same pair of stimulus patterns to block this persistence. The distractor stimulus consisted of two pairs of stimulus patterns producing unequivocally vertical and horizontal apparent motions, respectively. A pair of red discs of the same size as S1, with a horizontal centre-to-centre separation of 2 deg, was presented alternately three times at upper and lower positions 2 deg apart, with the same duration and ISI as those of the preceding test stimulus. Then, another pair of red discs separated vertically was presented at right and left positions alternately three times, in a similar way. Subjects' experience of these unequivocal apparent motions in two directions blocked the persistence of apparent motion in either direction.

In perceptual-grouping experiments, the stimulus pattern was presented for 3 s in each trial. The subject tilted or pulled the joystick according to whether the 16 stimulus elements were seen in 4 horizontal rows or 4 vertical columns. In the same way as in the apparent-motion experiment, the horizontal separation was varied in steps of 15 min of visual angle according to the subject's responses, while the vertical centre-to-centre separation was kept fixed at 2 deg.

In part 1, the standard stimulus element was a red, middle-luminance (0.3 cd m^{-2}), middle-size (42 min of visual angle) disc. In each of four stimulus series, the stimulus element was varied in three levels, including the standard, in either of colour, luminance, size, or shape, with the other attributes kept the same as the standard, as follows.

Colour-difference series: *Red* ($x = 0.58$, $y = 0.32$ in chromaticity), Green ($x = 0.23$, $y = 0.60$), and Blue ($x = 0.15$, $y = 0.06$).

Luminance-difference series: High (0.8 cd m^{-2}), *Middle* (0.3 cd m^{-2}), and Low (0.07 cd m^{-2}).

Size-difference series: Large (1 deg 24 min in diameter), *Middle* (42 min), and Small (21 min).

Shape-difference series: *Disc* (42 min in diameter), Square and Triangle with the same area as the Disc.

Here italics indicate the standard stimulus element. In each series, all nine combinations of the three variations of S1 and those of S2 were used.

In part 2, stimulus elements S1 were always the standard ones (red, middle-luminance, middle-size disc). Elements S2 were different from S1 in one to four attributes of colour, luminance, size, and shape. Stimulus differences were combined in 16 ways as shown in table 1. The chromaticities of Red and Green stimuli used in part 2 were $x = 0.61$, $y = 0.36$ for Red, and $x = 0.30$, $y = 0.58$ for Green. The luminance and size were exactly the same as those in part 1.

The luminance of the black background was kept at 0.1 cd m^{-2} in both parts.

Table 1. Stimulus elements S2 in part 2.

Number	Colour	Luminance	Size	Shape	Difference(s)
1	R	M	M	D	no
2	*G*	M	M	D	single
3	R	*H*	M	D	single
4	R	M	*L*	D	single
5	R	M	M	*T*	single
6	*G*	*H*	M	D	double
7	*G*	M	M	*T*	double
8	R	*H*	M	*T*	double
9	R	*H*	*L*	D	double
10	R	M	*L*	*T*	double
11	*G*	M	*L*	D	double
12	*G*	*H*	M	*T*	triple
13	*G*	*H*	*L*	D	triple
14	R	*H*	*L*	*T*	triple
15	*G*	M	*L*	*T*	triple
16	*G*	*H*	*L*	*T*	quadruple

Note: R, Red; G, Green; M, Middle; H, High; L, Large; D, Disc; T, Triangle. Symbols in italics indicate differences from S1.

2.3 *Procedure*

Half of the subjects were presented with the apparent-motion experiment in the first session, and then with the perceptual-grouping experiment in the second session. These were presented in reversed order for the remaining subjects. All stimulus pairs were presented twice in random order in each session. The measurement of matched separation was made for each presentation of each stimulus pair by the double staircase method, in which four points of response change were recorded for each of two parallel series of stimulus presentations and averaged. A 10-min dark adaptation period was inserted at the beginning of each session, and then some practice trials were given before experiments. A 30-min rest was inserted in the middle of the session. Another 10-min dark adaptation period was inserted again after the rest.

3 Results and discussion

The results of the present experiments generally indicated that apparent motion or perceptual grouping occurs between stimulus elements with different perceptual attributes (colour, brightness, size, and/or shape), separated vertically by a constant distance

(2 deg), with the same probability as it occurs between stimulus elements with the same perceptual attributes, but separated horizontally by a certain longer distance. This horizontal distance was measured in experiments and called the matched separation in a given condition.

In figures 3–6, the mean matched separation in apparent motion is plotted against the mean matched separation in perceptual grouping. Each dot represents a stimulus pair, and solid lines indicate regression lines of the matched separations in apparent motion (Y) to those in perceptual grouping (X). The vertical and horizontal bars attached to each dot indicate standard errors in apparent-motion and perceptual-grouping experiments, respectively. The results indicate that the matched separation increases as the perceptual difference between the heterogeneous stimulus elements increases, both in experiments on apparent motion and those on perceptual grouping.

For example, the matched horizontal separation increased greatly when the luminance difference between vertically separated elements increased from a smaller difference between Low (L) and Middle (M) or that between Middle (M) and High (H) to a

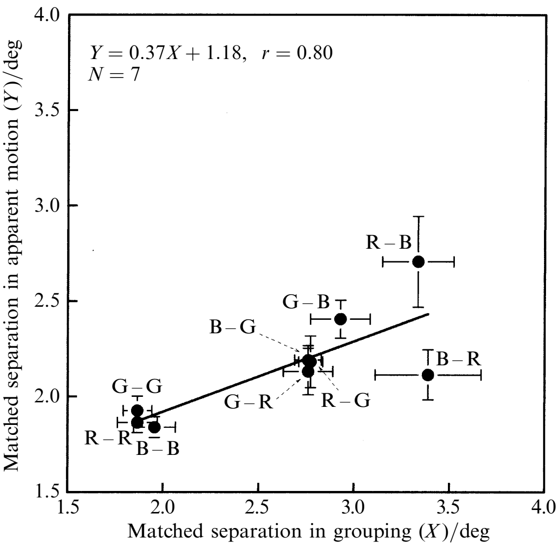

Figure 3. Results of the colour-difference series of part 1. Mean matched separation in apparent motion is plotted against mean matched-separation in perceptual grouping. Each dot represents a stimulus pair, and the solid line is the regression line. The vertical and horizontal bars denote standard errors in apparent motion and perceptual grouping, respectively. Symbols indicate stimulus pairs. For example, R–G means the pair of Red S1 and Green S2. R, Red; G, Green; B, Blue.

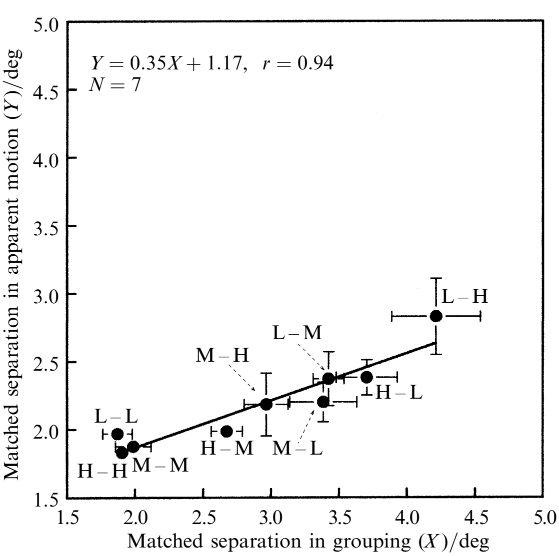

Figure 4. Results of the luminance-difference series of part 1. H, High; M, Middle; L, Low.

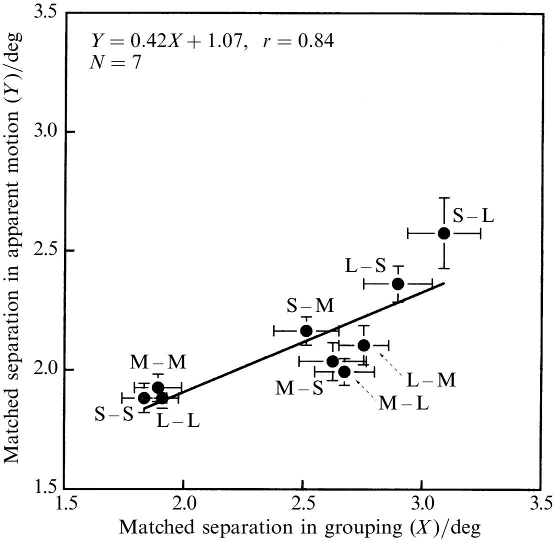

Figure 5. Results of the size-difference series of part 1. L, Large; M, Middle; S, Small.

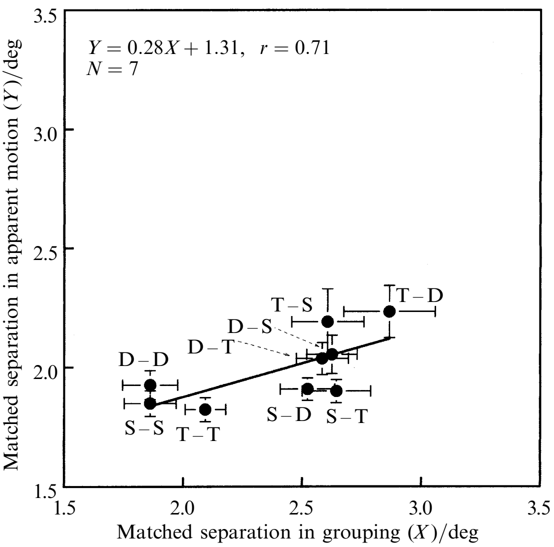

Figure 6. Results of the shape-difference series of part 1. D, Disc; S, Square; T, Triangle.

larger one between Low (L) and High (H). Similar tendency was also found in the size-difference series. In each of these two series, perceptual differences were varied on a linear scale, brightness or size, and easily predictable, at least in the order of difference magnitudes, whereas, in the colour and shape series, perceptual differences were varied multidimensionally and were not easily predictable. The present results provide data which can be used to compare perceptual differences in such complex perceptual attributes on a linear scale, ie matched separation.

Significant correlations (0.80, 0.94, 0.84, and 0.71, as shown in figures 3 to 6) of the matched separations were found between apparent motion and perceptual grouping in four stimulus series; colour, luminance, size, and shape of part 1 ($t_7 = 3.50$, 6.97, and 4.09; $p < 0.01$ for the colour, luminance, and size series, respectively; and $t_7 = 2.66$, $p < 0.05$ for the shape series). This suggests that the same similarity factor is working in both phenomena, apparent motion and perceptual grouping. However, the regression coefficients (0.37, 0.35, 0.42, and 0.28) are rather small throughout, although they are significant as shown by significant correlations (Cohen and Cohen 1983; McNemar 1962).

This means that the similarity or difference in the perceptual attributes affects perceptual grouping more strongly than it does apparent motion. The fact that the same similarity factor determines both apparent motion and perceptual grouping does not necessarily mean that apparent motion is a kind of perceptual grouping. Oyama and Yamada (1978) studied perceptual grouping between successively presented stimuli and found that the probability of grouping was a simple decreasing function of the asynchrony of these stimuli, while the probability of optimal apparent motion had been known to be an inverted-U-shaped function of the asynchrony (Kolers 1972). From this difference, they deduced mutual independence of these two phenomena.

In figures 3 – 6, one finds a trend for the matched separations for identical stimulus pairs (R – R, G – G, B – B, H – H, etc) to be smaller than the vertical separation (2.00). The differences are significant for four of the twelve stimulus pairs in apparent motion [B – B, H – H, L – L (in the size series), T – T, with $t_6 = 2.66$, 5.52, 2.55, and 3.22; $p < 0.01$ for H – H, and $p < 0.05$ for the others]. This might be caused by the intertrial distractor stimulus which always ended with vertical motion. The residual weak bias towards vertical motion would make the matched horizontal separation a little smaller. No significant difference has been found for identical stimulus pairs in perceptual grouping. There are also some discrepancies in plotted positions between equivalent reciprocal pairs (B – G, G – B; R – G, G – R; R – B, B – R; H – M, M – H; etc), but none of these reaches a significance level in the t-test for either phenomenon.

The results of the 150 ms duration/ISI condition in part 2 are shown in figure 7. Very similar results were obtained in the 80 and 100 ms duration/ISI conditions, although figures for them are not shown here. This similarity of results obtained in the three temporal conditions indicates that the finding of the present study is not specific to the rather long stimulus onset asynchrony used in part 1. The correlation coefficients (0.77, 0.88, 0.89, for the 80, 100, and 150 duration/ISI conditions, respectively) were always highly significant ($t_{14} = 4.51$, 7.15, 7.04; $p < 0.01$), and the regression coefficients (0.27, 0.36, 0.34) were also significant but again rather small.

These results indicate that the matched separation increases as the differences in different stimulus attributes, colour, luminance, size, and shape are combined to a greater and greater extent, from single differences to double, triple, and quadruple differences, in apparent motion as well as in perceptual grouping, although the effects were weaker in the former than the latter. This means that effects of similarities or differences work

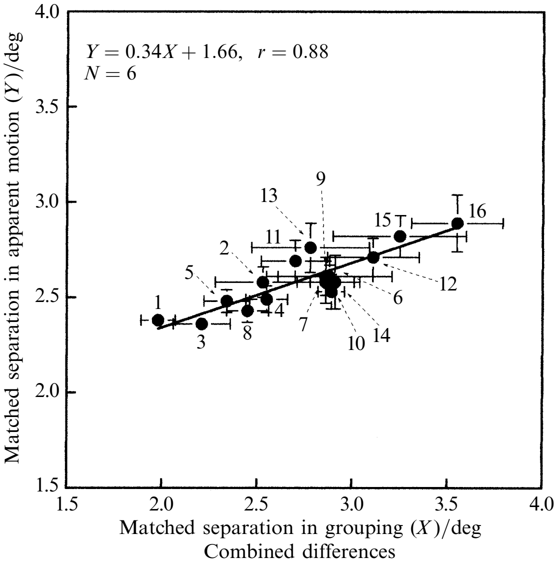

Figure 7. Results of the 150 ms duration/ISI condition in part 2. Numbers 1 to 16 indicate stimulus pairs listed in table 1.

additively across different perceptual attributes on both phenomena, as it has been shown partly by Caelli et al (1993) for apparent motion.

The results of these experiments confirm the tendency found for crossed phi by Oyama et al (1994), in the present experiments more quantitatively for single phi. As the difference in either colour, luminance, size, and shape in part 1, or their combinations in part 2, increased between heterogeneous stimulus elements, apparent motion, as well as perceptual grouping, tended to occur less easily between them. The separation between homogeneous stimulus elements had to be increased to match two different possible motions or groupings in the probabilities of occurrence.

These findings, especially those in part 1, are in line with those of Anstis and Mather (1985), Cavanagh et al (1989), Dobkins and Albright (1993), Green (1989), Mack et al (1989), Nishida and Takeuchi (1990)[(2)] in their experiment 3 (ambiguous motion display), Shechter et al (1988), Shechter and Hochstein (1989), and Ullman (1980) who studied the individual effects of similarity in colour, luminance, size, or shape on apparent motion, mostly from the point of view of the correspondence problem proposed by Ullman (1979). The correspondence problem is concerned with the one-to-one matching process between stimulus targets of successively presented frames.

However, we consider these findings from a broader point of view, in which spatial position is also regarded as one of the perceptual attributes in the same way as colour, brightness, size, and shape, as suggested by Foster (1978), Oyama (1997), Oyama et al (1994), and Shechter and Hochstein (1989). We consider that all similarities or differences in these perceptual attributes work together, as shown in the results of part 2 of the present study. If positional similarity (proximity) or difference (distance) is also one of the similarities or differences that work together with those in the other perceptual attributes, it is quite natural that a larger positional change (larger separation) is traded off against a larger or more complex perceptual change in targets. If apparent motion occurs between two rather distant targets with the same colour, the same brightness, the same size, and the same shape, no perceptual change occurs except positional change. In this sense, the perceptual constancy of objects is kept, owing to the apparent motion. Consequently, perceptual motion can be regarded as a manifestation of the general perceptual tendency to make perceptual changes as small as possible. This puts apparent motion in line with various perceptual constancies, as discussed by Oyama (1997). He pointed out, on the basis of experimental work by Oyama et al (1994), that apparent motion is only one of possible solutions of perceptual organisation that keep perceptual changes down to a minimum and maintain perceptual constancy as much as possible, and that apparent motion occurs when it can reduce the total perceptual changes more and make our perceptual world more stable than other possible percepts, such as sudden appearance and disappearance of objects in different positions.

He and Nakayama (1994) and Shimojo and Nakayama (1990) indicated that the effects of perceptual attributes on apparent motion are not determined at the early filtering level, but at a higher perceptual processing level, including that for amodally perceived surface shapes. This view is supported by the results of part 2 of the present study, in which the effects of the similarities in perceptual attributes such as colour and shape were combined together, indicating that their effects are determined at a higher level than the attribute-specific processing level.

It should also be noted that the experimental situations used in the present study, as in that of Shechter and Hochstein (1989), make it possible to compare perceptual differences across quite different perceptual attributes on the same scale, ie the matched separation between homogeneous stimulus elements. For example, an inspection of figures 3–6 suggests that the perceptual difference between red and green nearly corresponds to the perceptual difference between 0.3 to 0.8 cd m^{-2} luminance, that between 1 and 4

[(2)] See footnote 1.

size (area) difference, and that between triangle and square in matched separation, in both apparent motion and perceptual grouping. The present study indicates that luminance is as effective as size, as shown in Oyama et al (1994), whereas luminance was found to be less effective than size by Shechter and Hochstein (1989). More exact measurements of matched separations will make it possible to compare quantitatively relative contributions of similarities in various perceptual attributes on the two perceptual phenomena, on one hand, and to scale perceptual similarities multidimensionally in dynamic situations, on the other hand.

Shechter et al (1991) found interesting gender differences, namely that women are more sensitive to distance disparity, whereas men are more sensitive to differences in shape, in a bistable apparent motion display like the present study. Unfortunately, the number of the subjects in the present study was too small, four men and three women in part 1, and three men and three women in part 2, to analyse such gender differences.

The present study is primarily concerned with first-order motion in the sense of Cavanagh and Mather (1989). Our recent preliminary study on second-order motion defined by flicker or motion of random microtextures in a similar experimental situation suggested that the above discussion might be limited to first-order motion (Oyama et al 1998). Werkhoven et al (1993, 1994) indicated that similarity in spatial structure between elements in a texture-defined (second-order) motion path does not determine the motion strength. The effect of similarity on apparent motion should be investigated further in the context of the order-specificity and the functional architecture of human visual motion perception (Lu and Sperling 1995; Mather and Murdoch 1997, 1998; Nishida et al 1997).

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